

NA61/SHINE experiment at CERN SPS: Recent results, current status and perspectives

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Abstract. The NA61/SHINE experiment at the CERN SPS studies hadron production properties in hadron-nucleus and nucleus-nucleus collisions. Recent results from p+p, Be+Be and Ar+Sc interactions provide new data on the system size and energy dependence of hadron multiplicities, spectra and fluctuations. In particular, they indicate a threshold for formation of large clusters interpreted as the onset of fireball. A scaled-factorial-moment analysis of the proton density fluctuations in Ar+Sc collisions at 150A GeV/c shows an intermittency signal, which may be a first trace of critical behavior. The main objective of the future NA61/SHINE program is to obtain high-precision data on charm hadron production. This new program is planned to start in 2021, after the Long Shutdown 2 of the CERN accelerators. It requires significant upgrades of the NA61/SHINE detectors in order to increase the data readout rate tenfold.

1. Introduction

NA61/SHINE is a fixed-target experiment at the CERN Super-Proton-Synchrotron (SPS) measuring the hadron production in hadron-nucleus and nucleus-nucleus collisions with a large acceptance detector system [1]. The measurements performed for a wide range of reactions provide valuable data for studying properties of hadronic matter under extreme conditions. They also provide precise results on hadron production for determining the neutrino flux in long-baseline neutrino experiments and for more reliable simulations of cosmic-ray showers. The primary aim of the experiment is the investigation of the transition from hadron gas to quark-gluon plasma and the search for a possibly existing associated critical point. A broad region of the phase diagram of hadronic matter is probed by varying energy and size of the collision system (from p+p to Pb+Pb in the beam momentum range $13A \div 150A$ GeV/c). Various observables, e.g. quantities measuring event-to-event fluctuations of the particle multiplicity, which are expected to reveal the occurrence of a phase transition or of critical behavior are examined. The experimental program has recently been extended by measurements of charm hadron production in nucleus-nucleus collisions, which are expected to provide an additional insight into the phase transition behavior of hadronic matter. For this purpose, the experimental setup was supplemented with a vertex detector that allows for precise vertex reconstruction in the target proximity.



2. Recent results

2.1. Onset of deconfinement and onset of fireball

The observed maximum (horn) in the excitation function of the $\langle K^+ \rangle / \langle \pi^+ \rangle$ yield ratio in NA49 Pb+Pb reactions, located at the low CERN SPS energies, has been interpreted as an evidence of the onset of deconfinement [2]. Such an interpretation is based on predictions of the Statistical Model of the Early Stage (SMES), which contains a first-order phase transition from the hadron gas to the quark-gluon plasma [3]. A collection of available data on $\langle K^+ \rangle / \langle \pi^+ \rangle$ supplemented by recent NA61/SHINE results from p+p, Be+Be and Ar+Sc collisions is presented in Fig. 1. These new data track the appearance of the signal with increasing system size. The Be+Be results are similar to p+p and do not show any maximum. The Ar+Sc data lie between the light and heavy Pb+Pb/Au+Au systems (left panel). The Be+Be results are similar to p+p and do not show any maximum. The Ar+Sc data lie between the light and heavy Pb+Pb/Au+Au systems (left panel).

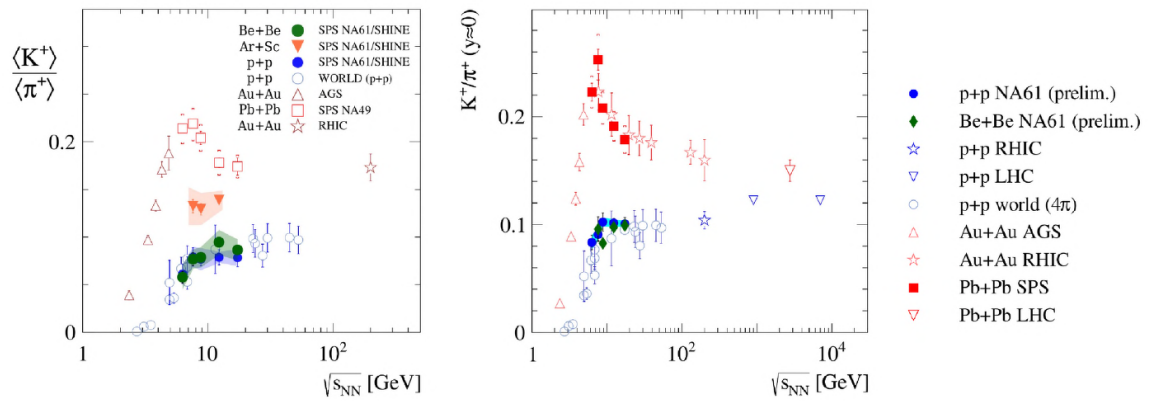


Figure 1. Energy dependence of the $\langle K^+ \rangle / \langle \pi^+ \rangle$ yield ratio in the full phase space (left panel) and at mid-rapidity (right panel).

Another indication of the onset of deconfinement suggested by the SMES model is a step structure (plateau) in the energy dependence of the inverse slope parameter T of the transverse mass distribution of K mesons. Such a structure has been observed in central Pb+Pb collisions as shown in Fig. 2. A trace of the step structure is also observed in the light p+p and Be+Be systems. The origin of this effect and its possible relation to the deconfinement transition remains to be clarified.

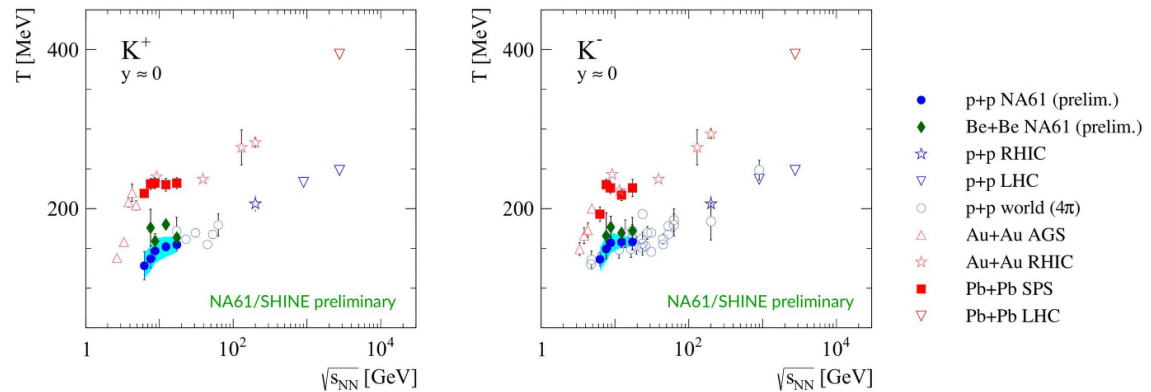


Figure 2. Energy dependence of the inverse slope parameter T of the transverse mass spectra of K^+ and K^- mesons measured at mid-rapidity.

Figure 3 shows the system size dependence of the K^+/π^+ ratio for three different collision energies. The p+p and Be+Be results are on the same level independently of the collision energy. They can be described by incoherent superposition of particles from wounded nucleons as predicted by the Wounded Nucleon Model [4]. When passing to heavier systems one observes a rapid increase towards the statistical model expectations. This effect can be interpreted as the onset of fireball, the beginning of formation of a large thermalized cluster.

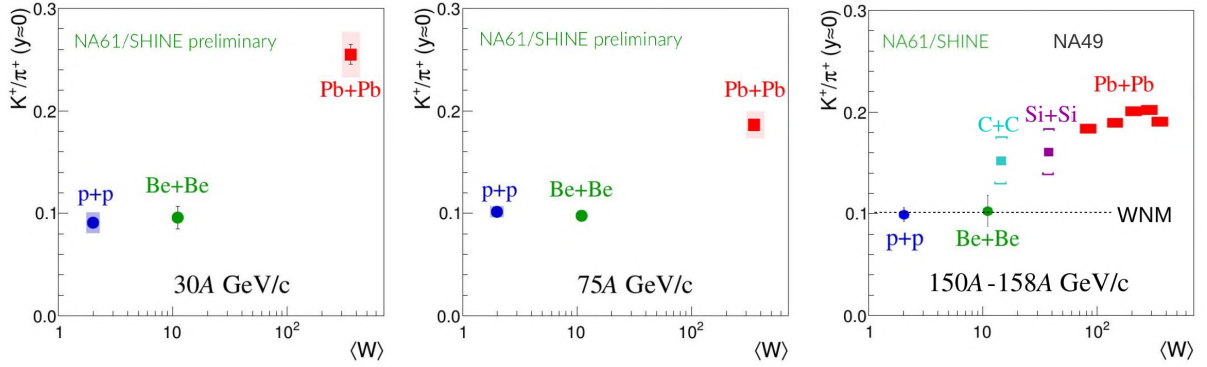


Figure 3. Dependence of the mid-rapidity K^+/π^+ ratio on the mean number of participant nucleons (or wounded nucleons) $\langle W \rangle$, observed at 30A, 75A and 150-158A GeV/c.

2.2. Search for the critical point

The ongoing criticality analysis is focused on event-to-event fluctuations of the particle multiplicity and transverse momentum, on Bose Einstein momentum correlations, and on proton density fluctuations. So far, the only signal which may be considered as a trace of critical behavior comes from an intermittency analysis of the proton density distribution in transverse momentum space at mid-rapidity. In this analysis, the transverse momentum space is partitioned into $M \times M$ equal-size bins, and the proton distribution is quantified by multiplicities in individual bins. If the system exhibits critical fluctuations, the second scaled factorial moment of the multiplicity distribution is expected to scale with M as a power-law: $F_2(M) \sim M^{2\phi_2}$, where ϕ_2 is the intermittency index [5].

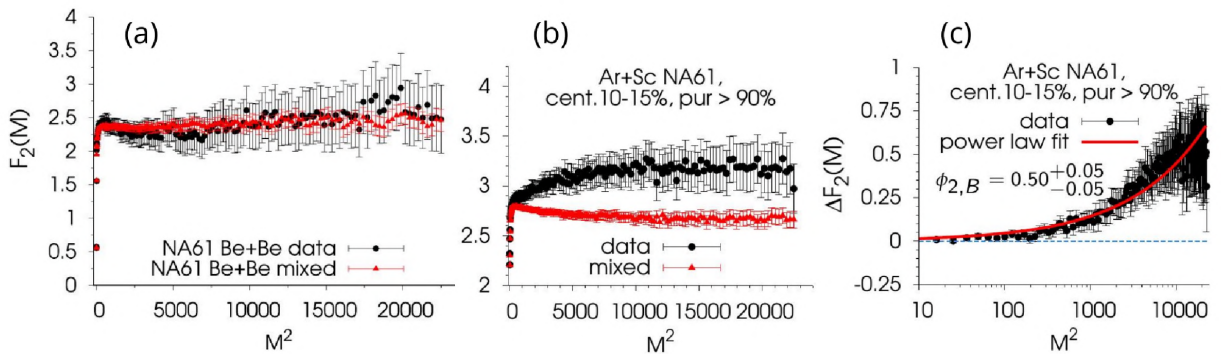


Figure 4. (a) $F_2(M)$ of protons at mid-rapidity measured in the 0-12% most central Be+Be collisions at 150A GeV/c (black points). The red points show results for mixed events. (b) As in (a) for 10-15% central Ar+Sc. (c) Power-law fit to the Ar+Sc background subtracted data (the differences between the black and red points in panel (b)).

Preliminary results on $F_2(M)$ for Be+Be and Ar+Sc systems at 150A GeV/c are shown in Fig. 4(a) and (b) by the black points. The experimental data require corrections for the presence of a background of uncorrelated and misidentified protons. The background was estimated by calculating $F_2(M)$ for mixed events and is shown in the figure by the red points. $F_2(M)$ values calculated for Be+Be data are at the background level, indicating no intermittency signal. In contrast, an intermittency effect is seen in mid-central Ar+Sc collisions at 150A GeV/c. The background subtracted $F_2(M)$ results with a power-law fit are shown in panel (c). This is similar to the effect observed by NA49 in central 'Si'+Si collisions at 158A GeV/c [6]. The analysis of Xe+La at 150A GeV/c as well as Ar+Sc at 75A GeV/c has the highest priority in NA61/SHINE as it might strengthen the evidence for the expected nonmonotonic system size and collision energy dependence of an intermittency signal from the critical point.

3. Open charm measurements

The NA61/SHINE charm program is an extension of the previous studies into the c-quark mass domain in order to learn about the mechanism of charm production in heavy-ion collisions and to gain a better insight into the phase transition to the quark-gluon plasma. To achieve these goals, knowledge on the mean number of charm quark-antiquark pairs $\langle c\bar{c} \rangle$ produced in the full phase space is required. Such data do not exist yet and NA61/SHINE plans to provide them within the coming years.

One of the important aspects of relativistic heavy-ion collisions is the mechanism of charm production. Several models were developed to describe charm production, based on dynamical and statistical approaches. Their predictions on the average number of c and \bar{c} pairs, $\langle c\bar{c} \rangle$, produced in central Pb+Pb collisions at 158A GeV/c differ up to two orders of magnitude, as shown in Fig. 5(a) [3, 7]. Measurements of $\langle c\bar{c} \rangle$ will allow to discriminate between them, and thus to learn about the charm quark and hadron production mechanism. A good estimate of $\langle c\bar{c} \rangle$ can be obtained by measuring the yields of D^0 , D^+ and their antiparticles because these mesons carry about 85% of the total produced charm [8].

Charm mesons are of special interest in the context of the phase transition between confined hadronic matter and the quark-gluon plasma (QGP). The production of charm is expected to be different in confined and deconfined matter, because of different properties of charm carriers in these phases. In confined matter the lightest charm carriers are D mesons, whereas in deconfined matter the carriers are charm quarks. The production of a $D\bar{D}$ pair ($2m_D = 3.7$ GeV) requires more energy (about 1 GeV) than production of a $c\bar{c}$ pair ($2m_c = 2.6$ GeV). Since the effective numbers of degrees of freedom of charm hadrons and charm quarks are similar [16], more abundant charm production is expected in deconfined than in confined matter. Consequently, in analogy to strangeness production [3, 17], a change in the collision energy dependence of $\langle c\bar{c} \rangle$ may reveal the onset of deconfinement.

Figure 5(b) presents the collision energy dependence of $\langle c\bar{c} \rangle$ in central Pb+Pb collisions predicted by the Statistical Model of the Early Stage [3]. According to this model, the phase transition from hadron gas to quark-gluon plasma can be indicated by a nonmonotonic enhancement of $\langle c\bar{c} \rangle$ production.

Figure 5(c) shows results on $\langle J/\psi \rangle$ production normalized to the mean multiplicity of Drell-Yan pairs $\langle DY \rangle$ in Pb+Pb collisions at the top SPS energy obtained by the NA50 collaboration. The solid line shows a model prediction for normal nuclear absorption of J/ψ in the medium [15]. NA50 observed that J/ψ production is consistent with normal nuclear matter absorption for peripheral collisions but is more suppressed in central collisions. This anomalous suppression was attributed to the J/ψ dissociation effect in the deconfined medium. However, the above result is based on the assumption that $\langle c\bar{c} \rangle \sim \langle DY \rangle$ which may be incorrect due to several effects, such as shadowing or parton energy loss [18, 19]. Thus the effect of the medium on $c\bar{c}$ binding can only be quantitatively determined by comparing the ratio of $\langle J/\psi \rangle$ to $\langle c\bar{c} \rangle$ in nucleus-nucleus

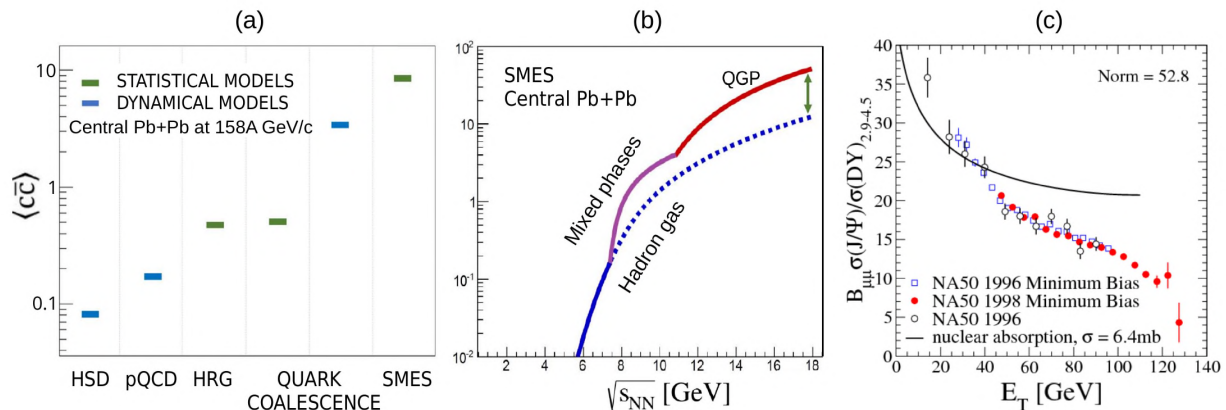


Figure 5. (a) Mean multiplicity of charm quark-antiquark pairs produced in the full phase space in central Pb+Pb collisions at 158A GeV/c calculated with dynamical models (blue bars): HSD [9, 10], pQCD-inspired [11, 12], and Dynamical Quark Coalescence [13], as well as statistical models (green bars): HRG [14], Statistical Quark Coalescence [14], and SMES [3]. (b) Energy dependence of $\langle c\bar{c} \rangle$ in central Pb+Pb collisions calculated within the SMES model [3]. The blue line corresponds to confined, the purple line to mixed phase, and the red line to deconfined matter. The dashed line presents the prediction without a phase transition. (c) The ratio of $\sigma_{J/\psi}/\sigma_{DY}$ as a function of the transverse energy (a measure of collision violence or centrality) in Pb+Pb collisions at 158A GeV measured by NA50. The curve represents the J/ψ suppression due to ordinary nuclear absorption [15].

to that in proton-proton reactions. In Pb+Pb collisions the onset of color screening should be seen as a decrease of the $\langle J/\psi \rangle$ to $\langle c\bar{c} \rangle$ ratio for more central collisions. This motivates the need for obtaining reliable experimental data on $\langle c\bar{c} \rangle$.

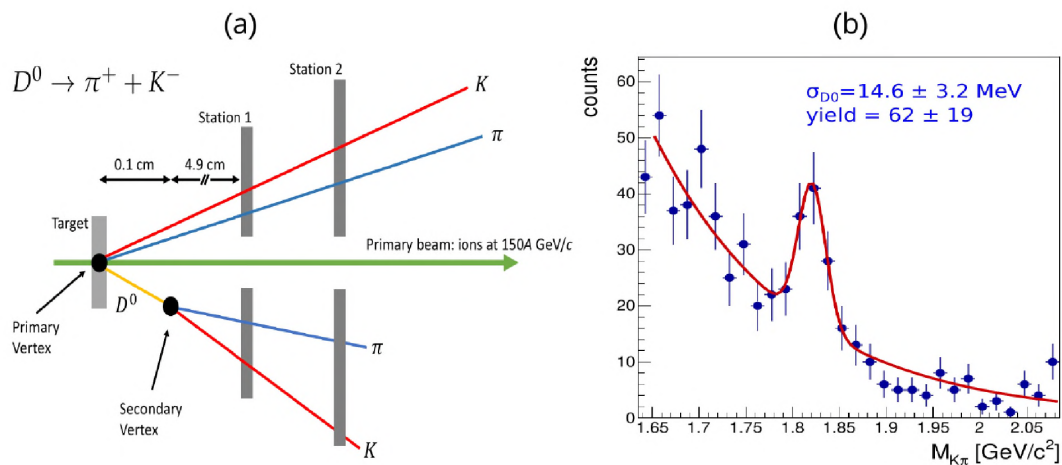


Figure 6. (a) Schematics of reconstruction of a $D^0 \rightarrow \pi^+ + K^-$ decay with help of Vertex Detector. (b) Invariant mass distribution of D^0 and \bar{D}^0 candidates in central Pb+Pb collisions at 150A GeV/c after applying background suppression cuts.

The first measurements of open charm production were performed in December 2016 during a Pb+Pb test run, using a new high-resolution vertex detector [20]. Its role in measurements of charm D^0 mesons via their hadronic decay channel is schematically shown in Fig. 6(a).

Identification of the daughter particles of D^0 is based on measuring the separation between the primary and decay vertices. Due to the Lorentz boost, the average separation is about 1 mm. Figure 6(b) shows the first indication of a D^0 or \bar{D}^0 peak in the invariant mass distribution obtained from these measurements.

Successful performance of this detector led to the decision to use it during the Xe+La data taking in 2017 and Pb+Pb run in 2018. The collected Xe+La data are currently under analysis and are expected to lead to physical results in the coming months. Precise measurements of various open charm mesons produced in Pb+Pb collisions, which will allow determining $\langle c\bar{c} \rangle$ are planned for the years 2021-2024.

4. Physics program for 2021-2024 and planned detector upgrades

NA61/SHINE plans precise measurements of hadron and nuclear fragment production properties in reactions induced by hadron and ion beams after the Long Shutdown 2 of the CERN accelerators [7]. The measurements are requested by heavy ion, cosmic ray and neutrino communities and they will include:

- measurements of charm hadron production in Pb+Pb collisions for heavy ion physics,
 - measurements of nuclear fragmentation cross sections for cosmic ray physics,
 - measurements of hadron production induced by proton and kaon beams for neutrino physics.
- NA61/SHINE is the only experiment which will conduct such measurements in the near future in the CERN SPS beam momentum range.

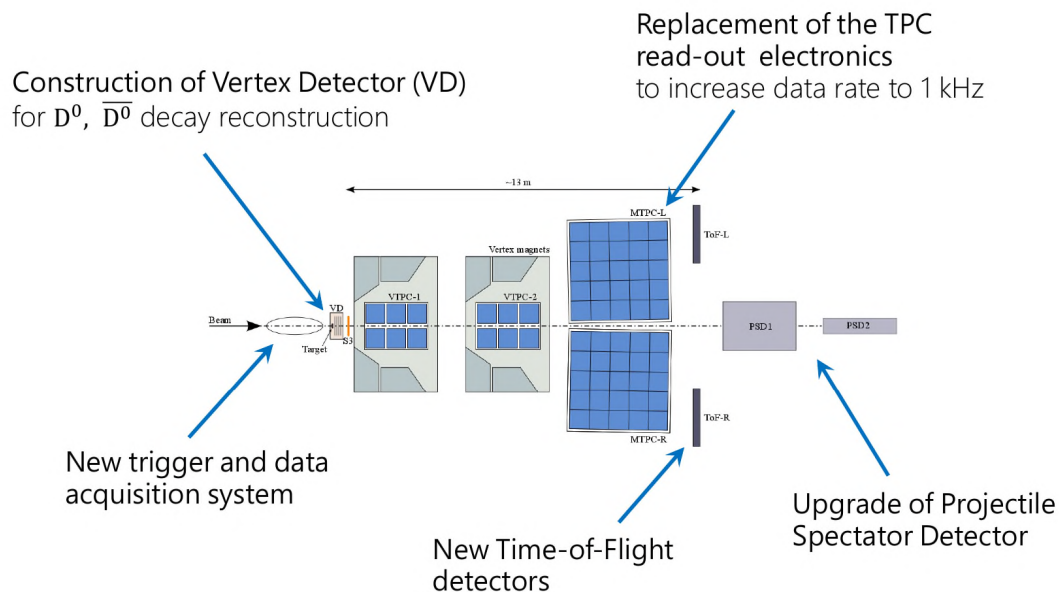


Figure 7. Upgrades of the NA61/SHINE detectors planned to be completed during the Long Shutdown 2 period.

The realization of this program requires a significant modification of the NA61/SHINE spectrometer. The upgrade is primarily motivated by the charm program which requires a tenfold increase of the data read-out rate to about 1 kHz and an increase of the phase-space coverage of the Vertex Detector by a factor of about 2. This requires construction of a new Vertex Detector, replacement of the TPC read-out electronics, implementation of new trigger and data acquisition systems, and upgrade of the Projectile Spectator Detector. Finally, new ToF detectors are planned to be constructed for particle identification at mid-rapidity. This is

mainly motivated by possible future measurements related to the onset of fireball. The detector upgrades are graphically summarized in Fig. 7. With the upgraded NA61/SHINE spectrometer, one expects that during one day of data taking $6 \cdot 10^6$ Pb+Pb collisions at $150A$ GeV/c will be collected. The current and planned data taking rates in NA61/SHINE and other heavy-ion experiments are compared in Fig. 8.

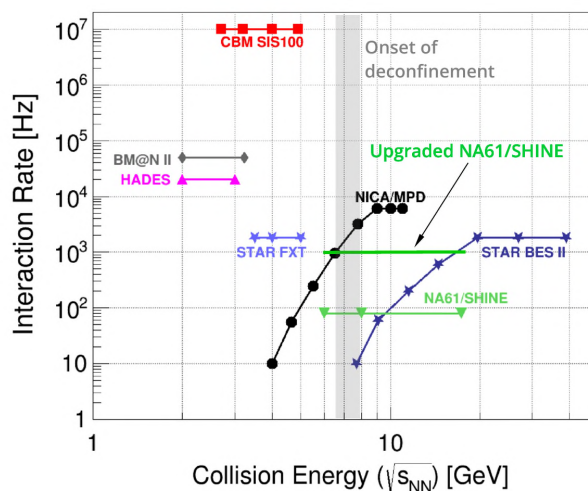


Figure 8. Interaction rates achieved by existing and planned heavy-ion experiments as a function of the center-of-mass energy (based on Fig. 3 in Ref. [21]).

Acknowledgments

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References

- [1] Abgrall N *et al.* 2014 *JINST* **9** P06005
- [2] Alt C *et al.* 2008 *Phys. Rev. C* **77** 024903
- [3] Gaździcki M and Gorenstein M I 1999 *Acta Phys. Pol. B* **30** 2705
- [4] Białas A, Bleszyński M and Czyż W 1976 *Nucl. Phys. B* **11** 461
- [5] Antoniou N G, Diakonos F K, Kapoyannis A S and Kousouris K S 2006 *Phys. Rev. Lett.* **97** 032002
- [6] Anticic T *et al.* 2015 *Eur. Phys. J. C* **75** 587
- [7] Aduszkiewicz A *et al.* Preprint CERN-SPSC-2017-038/CERN-SPSC-2018-008/SPSC-P-330-ADD-10
- [8] Cassing W and Bratkovskaya E L 2009 *Nucl. Phys. A* **831** 215
- [9] Linnyk O, Bratkovskaya E L and Cassing W 2008 *Int. J. Mod. Phys. E* **17** 1367
- [10] Song T private communication
- [11] Gavai R, Kharzeev, H. Satz, G. A. Schuler, K. Sridhar and R. Vogt 1995 *Int. J. Mod. Phys. A* **10** 3043
- [12] Braun-Munzinger P and Stachel J 2000 *Phys. Lett. B* **490** 196
- [13] Lévai P, Biró T S, Csizmadia P, Csörgő T and Zimányi J 2001 *J. Phys. G* **27** 703
- [14] Kostyuk A P, Gorenstein M I, Stöcker H, Greiner W 2002 *Phys. Lett. B* **531** 195
- [15] Abreu M C *et al.* 2000 *Phys. Lett. B* **477** 28
- [16] Poberezhnyuk R V, Gaździcki M and Gorenstein M I 2017 *Acta Phys. Pol. B* **48** 1461
- [17] Rafelski J and Müller B 1982 *Phys. Rev. Lett.* **48** 1066
- [18] Satz H 2014 *EPJ Web Conf.* **71** 00118
- [19] Satz H 2013 *Adv. High Energy Phys.* **2013** 242918
- [20] Deveau M *et al.* 2018 *EPJ Web of Conf.* **171** 10003
- [21] Ablyazimov T *et al.* 2017 *Eur. Phys. J. A* **53** 60